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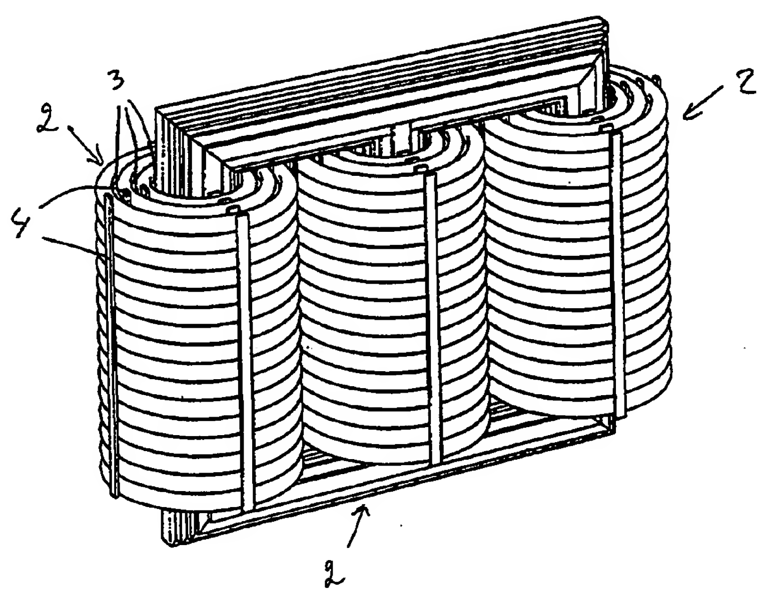
(54) Title: AXIAL AIR-COOLING OF TRANSFORMERS



(57) Abstract

A power transformer (1) comprising a transformer core wound with a high-voltage cable, which is composed of a core having a plurality of strand parts (112), an inner semiconducting layer (113) surrounding the core, an insulating layer (114) surrounding the inner semiconducting layer (113), and an outer semiconducting layer (115) surrounding the insulating layer (114) wherein the winding is provided with spacers (4, 12) arranged to separate each cable turn in radial direction in the winding in order to create axial cylindrical cooling ducts (3).

Axial air-cooling of transformers

TECHNICAL FIELD:

The present invention relates to an air-cooled, conductor-wound power transformer and to a method of air-cooling conductor-wound power transformers.

BACKGROUND ART:

Modern power transformers are usually oil-cooled. The core, consisting of a number of core legs joined by yokes, and the windings (primary, secondary, control), are immersed in a closed container filled with oil. Heat generated in coils and core is removed by the oil circulating internally through coils and core. The oil circulates out to an external unit where it is cooled. The oil circulation may either be forced, the oil being pumped around, or it may be natural, produced by temperature differences in the oil. The circulating oil is cooled externally by arrangements for air-cooling or water-cooling. External air-cooling may be either forced or through natural convection. Besides its role as conveyor of heat, the oil also has an insulating function in oil-cooled transformers for high voltage.

Dry transformers are usually air-cooled. They are usually cooled through natural convection since today's dry transformers are used at low power loads. The present technology relates to axial cooling ducts produced by means of a pleated winding as described in GB 1,147,049, axial ducts for cooling windings embedded in casting resin as described in EP 83107410.9, and the use of cross-current fans at peak loads as described in SE 7303919-0.

The cooling requirement is greater for a conductor-wound power transformer. Forced convection is necessary to satisfy the cooling requirement in all the windings. Natural convection is not sufficient to cool the conductor windings. A short transport route for the heat to the coolant is important, and also that it is efficiently transferred to the coolant. It is

therefore important that all windings are in direct contact with sufficient quantities of coolant.

A conductor is known through US 5 036 165, in which the insulation is provided with an inner and an outer layer of semiconducting pyrolized glassfiber. It is also known to provide conductors in a dynamo-electric machine with such an insulation, as described in US 5 066 881 for instance, where a semiconducting pyrolized glassfiber layer is in contact with the two parallel rods forming the conductor, and the insulation in the stator slots is surrounded by an outer layer of semiconducting pyrolized glassfiber. The pyrolized glassfiber material is described as suitable since it retains its resistivity even after the impregnation treatment.

OBJECT OF THE INVENTION:

The object of the invention is to provide a device according to the present claims, i.e. of the type described in the introduction which will enable air-cooling of a cable-wound power transformer comprising a high-voltage conductor of the type presented in the description. In a first embodiment, the invention aims at producing axial cylindrical ducts between each turn of the winding in windings where the coolant is correctly distributed in order to satisfy different cooling requirements of the windings. The cylindrical ducts are created by inserting spacers during winding of the coil. The flow of coolant is achieved with fans and the spacers are dimensioned to provide a flow through the ducts which will satisfy the cooling requirements of the individual windings.

SUMMARY OF THE INVENTION:

The present invention relates to a power transformer comprising a transformer core wound with cable, arranged so that the winding is provided with spacers separating each cable turn in radial direction in the winding in order to create axial cylindrical ducts.

A first embodiment of the invention thus comprises axial cylindrical cooling ducts between each winding turn placed one above the other, said ducts being created by spacers being inserted during winding of the coil. A cylindrical duct is also arranged between the legs of the core and the first layer of cable nearest the core. The embodiment also comprises fans for transporting air through the axial cylindrical ducts. The spacers in the ducts are dimensioned to give varying resistance, thus distributing the flow of coolant so that it covers the cooling requirement in the individual axial ducts since the cooling requirement is different for the windings. In spite of the fact that "air" is mentioned as coolant, also other gas coolants are suitable, for example helium gas coolant.

In a power transformer according to the invention the windings are composed of cables having solid, extruded insulation, of a type now used for power distribution, such as XLPE-cables or cables with EPR-insulation. Such a cable comprises an inner conductor composed of one or more strand parts, an inner semiconducting layer surrounding the conductor, a solid insulating layer surrounding this and an outer semiconducting layer surrounding the insulating layer. Such cables are flexible, which is an important property in this context since the technology for the device according to the invention is based primarily on winding systems in which the winding is formed from cable which is bent during assembly. The flexibility of a XLPE-cable normally corresponds to a radius of curvature of approximately 20 cm for a cable 30 mm in diameter, and a radius of curvature of approximately 65 cm for a cable 80 mm in diameter. In the present application the term "flexible" is used to indicate that the winding is flexible down to a radius of curvature in the order of four times the cable diameter, preferably eight to twelve times the cable diameter.

Windings in the present invention are constructed to retain their properties even when they are bent and when they are subjected to thermal stress during operation. It is vital that the layers retain their adhesion to each other in this context. The material properties of the layers are decisive here, particularly their elasticity and relative coefficients of thermal expansion. In a XLPE-cable, for instance, the insulating layer consists of cross-linked, low-density polyethylene, and the semiconducting layers consist of polyethylene with soot and metal particles mixed in. Changes in volume as a result of temperature fluctuations are completely absorbed as changes in radius in the cable and, thanks to the comparatively slight difference between the coefficients of thermal expansion in the layers in relation to the elasticity of these materials, the radial expansion can take place without the adhesion between the layers being lost.

The material combinations stated above should be considered only as examples. Other combinations fulfilling the conditions specified and also the condition of being semiconducting, i.e. having resistivity within the range of 10^{-1} - 10^{6} ohm-cm, e.g. 1-500 ohm-cm, or 10-200 ohm-cm, naturally also fall within the scope of the invention.

The insulating lay may consist, for example, of a solid thermoplastic material such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polybutylene (PB), polymethyl pentene (PMP), cross-linked materials such as cross-linked polyethylene (XLPE), or rubber such as ethylene propylene rubber (EPR) or silicon rubber.

The inner and outer semiconducting layers may be of the same basic material but with particles of conducting material such as soot or metal powder mixed in.

The mechanical properties of these materials, particularly their coefficients of thermal expansion, are affected

relatively little by whether soot or metal powder is mixed in or not - at least in the proportions required to achieve the conductivity necessary according to the invention. The insulating layer and the semiconducting layers thus have substantially the same coefficients of thermal expansion.

Ethylene-vinyl-acetate copolymers/nitrile rubber, butyl graft polyethylene, ethylene-butyl-acrylate-copolymers and ethylene-ethyl-acrylate copolymers may also constitute suitable polymers for the semiconducting layers. Even when different types of material are used as base in the various layers, it is desirable for their coefficients of thermal expansion to be substantially the same. This is the case with combination of the materials listed above.

The materials listed above have relatively good elasticity, with an E-modulus of E<500 MPa, preferably <200 MPa. The elasticity is sufficient for any minor differences between the coefficients of thermal expansion for the materials in the layers to be absorbed in the radial direction of the elasticity so that no cracks or other damage appear and so that the layers are not released from each other. The material in the layers is elastic, and the adhesion between the layers is at least of the same magnitude as the weakest of the materials.

The conductivity of the two semiconducting layers is sufficient to substantially equalize the potential along each layer. The conductivity of the outer semiconducting layer is sufficiently large to contain the electrical field in the cable, but sufficiently small not to give rise to significant losses due to currents induced in the longitudinal direction of the layer.

Thus, each of the two semiconducting layers essentially constitutes one equipotential surface, and these layers will substantially enclose the electrical field between them. There

is, of course, nothing to prevent one or more additional semiconducting layers being arranged in the insulating layer.

BRIEF DESCRIPTION OF THE DRAWINGS:

The invention will now be described in more detail with reference to the accompanying drawings.

Figure 1 shows one embodiment of a power transformer according to the invention, in perspective.

Figure 2a shows a view from above of the windings with cooling ducts, spacers and outer cover in a first embodiment according to the present invention.

Figure 2b shows a side view of the embodiment in Figure 2a provided with one fan per coil.

Figure 3 shows a section through a coil according to the embodiment in Figure 1 with its axial ducts between the windings.

Figure 4 shows a section through a high-voltage cable according to the present invention.

DESCRIPTION OF THE INVENTION:

Figure 1 shows an embodiment of the invention relating to a power transformer 1 provided with three winding coils 2, each having a number of windings arranged in winding turns radially separated by axial spacers 4 to produce axial concentric cooling ducts 3. The transformer is provided with an iron core in conventional manner.

Figure 2a shows a view from above of a three-phase power transformer 1 provided with windings 2 constituting coils with cooling ducts 3 produced by axially extending spacers 4 placed between each radially-lying turn of the winding. The distribution between the spacers 4 in the embodiment shown is such that six spacers are obtained in each concentric cooling duct 3. From the cooling aspect the shape and material of the spacers are of minor significance. The mechanical, magnetic and electrical aspects of the transformer determine the shape,

number and material of the spacers. The figure also shows the yoke 5 of the transformer, which constitutes a part of its iron core. The yoke is shown in section with its longitudinal cooling tubes 6 indicated. Each winding coil is also surrounded by a fan duct 7 inside which cooling air is arranged to flow. The cooling requirement is different for the windings, which means that the cooling flows in the concentric ducts differ. To achieve a correct distribution of coolant the ducts have different dimensions in radial direction in order to give different resistance in the ducts and thus distribute the flow in accordance with the needs of the ducts. Ducts with little cooling requirement thus have a smaller radial distance than ducts with greater cooling requirement which therefore have a larger radial distance. The cable-wound transformer described in the embodiment has larger spacing between the low-voltage windings, the windings closest to the core, than between the high-voltage windings.

Figure 2b shows a side view of the power transformer in Figure 2a, provided with corresponding windings and a corresponding yoke 5 together with its three legs 8 forming the iron core. The fan duct 7 is at one end of the coils and forms a fan cowl 9 in which at least one fan 10 is mounted. The embodiment in the figure shows three fans, closed in relation to their respective coils, in order to produce air flow in the axial cylindrical cooling ducts 3. The coils are encased in an outer cylindrical casing 11 to prevent radial leakage of air and to guide the air axially through the coils. The casing 11 around the outermost cable winding produces an outer duct for cooling of the outer part of the outermost cable winding. In this embodiment, it is also clear that a fan is mounted for each coil. The air can be withdrawn from or forced through the coil by each fan 10. The fan duct 7 at the side of the coil opposite to the fan 10 is completely open for air to flow either in or out depending on the suction or pressure function of the fan. The fan duct 7 on the fan side is provided with openings having a corresponding function.

Figure 3 shows a cross section of a coil with axial cylindrical cooling ducts 3 between each radial winding 2. Spacers are also arranged to form an axial cooling duct between the legs 8 of the core and the winding nearest the core. The cooling ducts are created by the spacers placed between the windings, see Figure 2a. The spacers are placed around the circular cross section and run in axial direction. The spacers are placed between the turns of the winding while the coil is being wound. The arrows in the figure indicate air flow through the windings of the coil. The air can flow in either direction, depending on the suction or pressure action.

Figure 4 shows a cross-sectional view of a high-voltage cable 111 for use as transformer winding in accordance with the present invention. The high-voltage cable 111 comprises a number of strands 112 of copper (Cu), for instance, having circular cross section. These strands 112 are arranged in the middle of the high-voltage cable 111. Around the strands 112 is a first semi-conducting layer 113. Around the first semi-conducting layer 113 is an insulating layer 114, e.g. XLPE insulation. Around the insulating layer 114 is a second semi-conducting layer 115. Thus the concept "high-voltage cable" in the present application does not include the outer sheath that normally surrounds such cables for power distribution. The high-voltage cable has a diameter within the range of 20-250 mm and a conducting area within the range of 40-3000 mm^2.

The invention is not limited to the examples shown. Several modifications are feasible within the scope of the invention. A fan need not be provided for each coil, for instance. An arrangement is feasible with one fan supplying all three coils with sufficient air. The air can be either sucked in or forced through the coils in order to achieve the desired cooling. Similarly, neither the number of spacers nor their shape is fixed and several different spacer variants are possible to

achieve the correct cooling. Neither need the spacers in the first embodiment described run entirely axially but may be placed in several ways.

Another modification is to arrange speed control of the fan with the aid of temperature sensors in order to enable a varied cooling requirement, depending on the load in the transformer.

The casing may also be arranged in a number of other ways than shown in the embodiments described above. The outermost cable winding can be used as outer casing and cool the outside by means of natural convection.

CLAIMS

1. A power transformer (1) comprising a transformer core, characterized in that the core is wound with a cable and that the cable is a high-voltage cable (111) which is composed of a core having a plurality of strand parts (112), an inner semiconducting layer (113) surrounding the core, an insulating layer (114) surrounding the inner semiconducting layer (113), and an outer semiconducting layer (115) surrounding the insulating layer (114) and that the winding is provided with spacers (4, 12) arranged to separate each cable turn in radial direction in the winding in order to create axial cylindrical cooling ducts (3).

2. A power transformer as claimed in claim 1, characterized in that the spacers (4, 12) are arranged axially between each turn of the winding.

3. A power transformer as claimed in claim 2, characterized in that at least six spacers (4) are distributed uniformly around the legs (8) of the transformer.

4. A power transformer as claimed in any of claims 1-3, characterized in that the transformer winding is provided with a fan cowl (9) sealing against one end of the outermost turn of the winding, to which a fan (10) is connected and arranged to either force gas, such as air, through or withdraw gas, such as air, air from all turns of the winding axially to the transformer core (8).

5. A power transformer as claimed in any of the claims 1-4, characterized in that the high-voltage cable (111) has a diameter within the interval of 20 - 250 mm and a conducting area within the interval of 40 - 3000 mm^2.

6. A power transformer as claimed in any of claims 1-5, characterized in that the cable (111) is flexible and the layers abut one another.

7. A power transformer as claimed in any of claims 1-6, characterized in that said layers are of materials having such elasticity and such coefficient of thermal expansion that the changes in volume in the layers caused by temperature fluctuations during operation are absorbed by the elasticity of the material, the layers thus retaining their adhesion to each other upon the temperature fluctuations that occur during operation.

8. A power transformer as claimed in any of claims 1-7, characterized in that the material in said layers has high elasticity, preferably with a modulus of elasticity less than 500 MPa, preferably less than 200 MPa.

9. A power transformer as claimed in any of claims 1-8, characterized in that the coefficients of thermal expansion for the materials in said layers are substantially the same.

10. A power transformer as claimed in any of claims 1-9, characterized in that the adhesion between layers is of at least the same magnitude as in the weakest of the materials.

11. A power transformer as claimed in any of claims 1-10, characterized in that each of the semiconducting layers essentially constitutes one equipotential surface.

12. A method of air-cooling a cable-wound power transformer according to any of the previous claims, characterized in that at least one fan (10) forces or withdraws air along the surface of the legs (8) of the transformer core and axially between each turn of the winding.

13. A method as claimed in claim 12, characterized in that spacers (4) are inserted between the winding turns during winding of the transformer.

14. A method as claimed in claim 13, characterized in that temperature sensors control the speed of the fan to produce a suitable air flow.

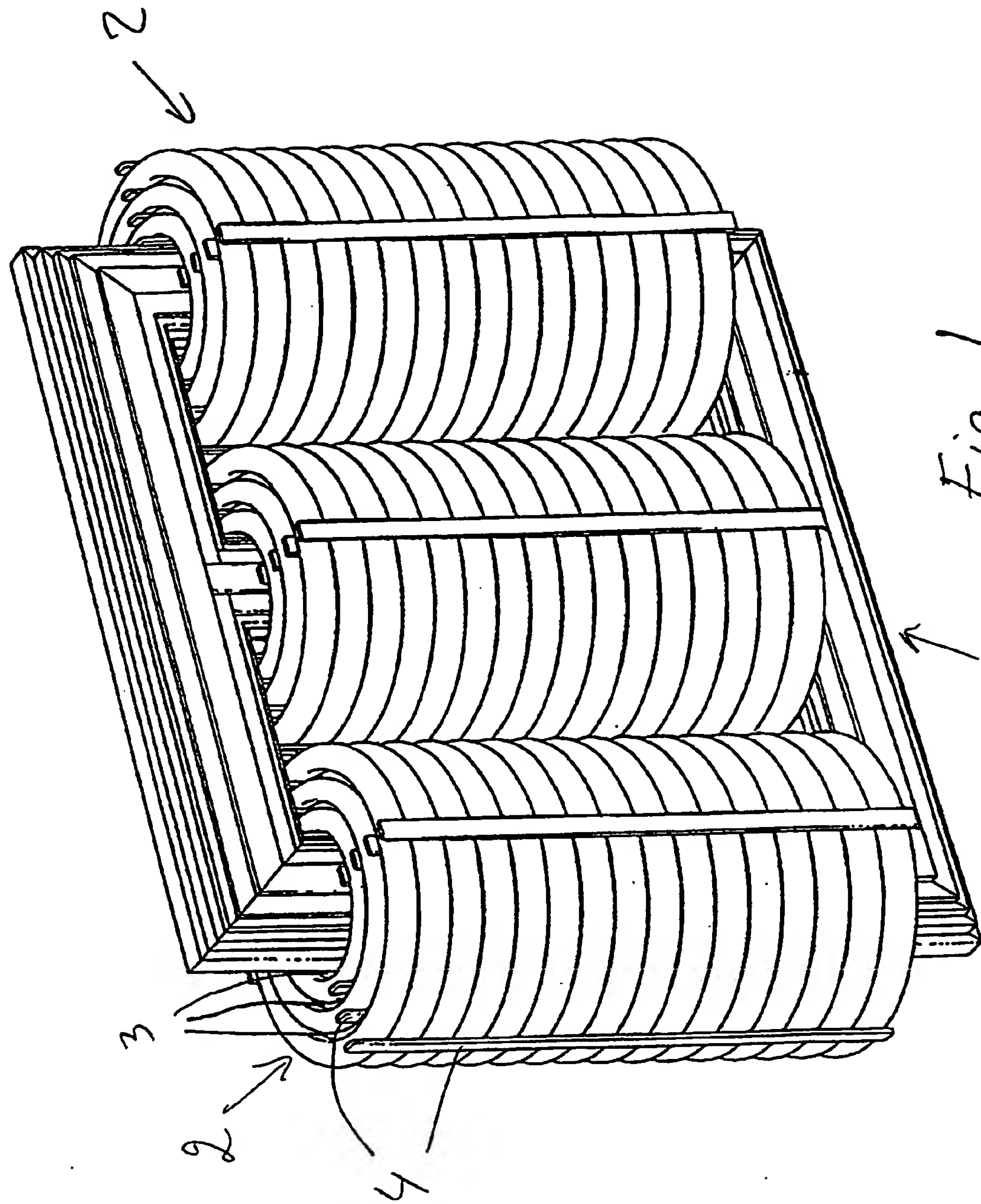


Fig. 1

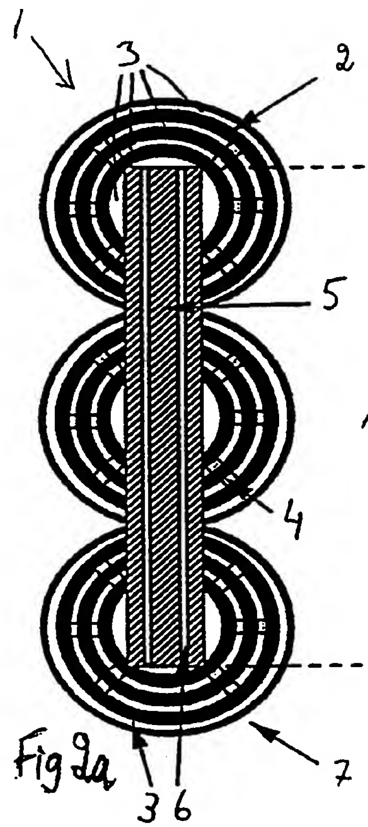


Fig 2a

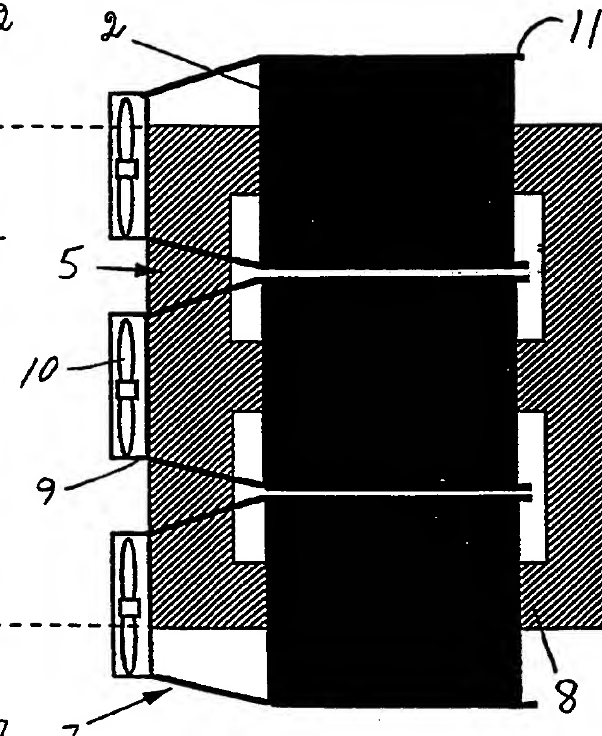


Fig. 2b

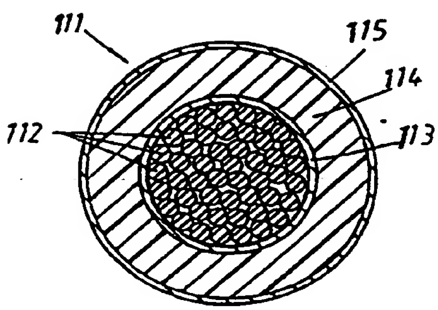


Fig. 4

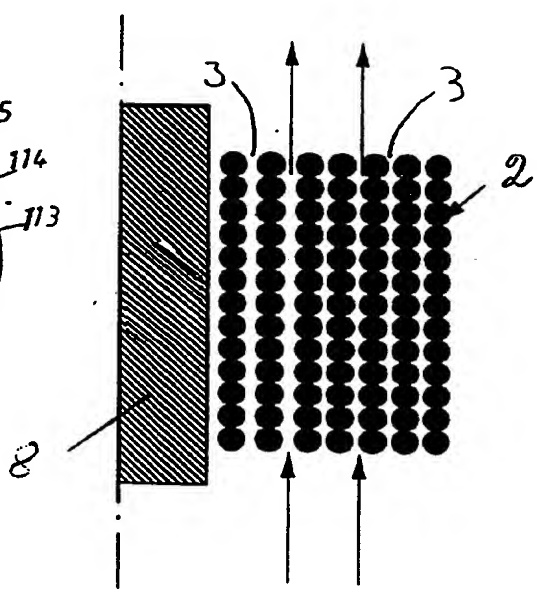


Fig. 3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 98/00155

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: H01F 27/08
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EDOC, WPIL, JAPIO

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2295415 A (G.R. MONROE), 8 Sept 1942 (08.09.42), page 2, line 22 - line 31, figure 4	1
A	US 5036165 A (RICHARD K. ELTON ET AL), 30 July 1991 (30.07.91), abstract	1

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
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- "Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 June 1998	23 -06- 1998

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INTERNATIONAL SEARCH REPORT

Information on patent family members

29/04/98

International application No.
PCT/SE 98/00155

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2295415 A	08/09/42	NONE	
US 5036165 A	30/07/91	US 5066881 A	19/11/91
		US 5067046 A	19/11/91
		CA 1245270 A	22/11/88
		US 4853565 A	01/08/89